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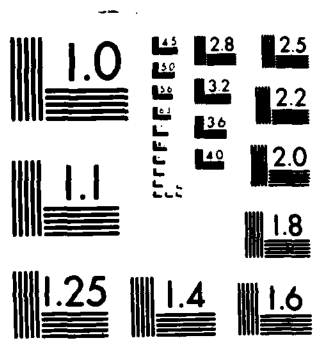
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MODEL FOR HIGH-SPEED INTERACTION HEATING

Annual Report

For the period

October 1, 1981 - September 30, 1982

H. Legner and M. Finson

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A boundary-layer model with application to high-speed flow separation in compression corner geometries is described. Integration through regions of separating/reattaching flow is facilitated through the use of an inverse boundary layer procedure that computes the pressure gradient for a given boundary-layer displacement thickness and displacement mass flow. Comparisons with Navier-Stokes calculations for a confined separated flow, using the Reyhner-Flügge-Lotz approximation in the reverse flow region, are good and

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have served to validate the boundary-layer approach. The viscous-inviscid interaction occurring in these flows are accounted for with the physically-sound coupling scheme developed recently by Wigton and Holt. A specific algorithm for hypersonic shock wave boundary-layer interactions is developed using the Newtonian flow approximation. Future calculations appropriate to laminar and turbulent compression corner experimental data are outlined.

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ABSTRACT

A boundary-layer model with application to high-speed flow separation in compression corner geometries is described. Integration through regions of separating/reattaching flow is facilitated through the use of an inverse boundary layer procedure that computes the pressure gradient for a given boundary-layer displacement thickness and displacement mass flow. Comparisons with Navier-Stokes calculations for a confined separated flow, using the Reyhner-Flügge-Lotz approximation in the reverse flow region, are good and have served to validate the boundary-layer approach. The viscous-inviscid interaction occurring in these flows are accounted for with the physically-sound coupling scheme developed recently by Wigton and Holt. A specific algorithm for hypersonic shock wave boundary-layer interactions is developed using the Newtonian flow approximation. Future calculations appropriate to laminar and turbulent compression corner experimental data are outlined.

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1. INTRODUCTION

This annual report describes the progress and current status of the Physical Sciences research effort on "Model for Turbulent Heating in High Speed Flows." The research studies emphasize two areas: (i) turbulent shock-wave boundary-layer interaction heating and (ii) effects of roughness on turbulent boundary-layer heating.

The emphasis in the research is on the development of improved theoretical methods for predicting turbulent compression-surface heating, primarily associated with control surfaces. Heating rates can be critically high on such surfaces. The compression process invariably involves significant increases in heat transfer (and skin friction) coefficient and, when boundary layer separation occurs, extremely high local heating rates have been observed near the reattachment point. Two generic geometries are being investigated. The two-dimensional geometry (e.g., a "flap") has been emphasized initially and forms the basis of our forthcoming three-dimensional investigations, such as would occur with a fin or skewed wedge.

The approach that is being used to model turbulent compression surface flows involves a second-order closure formulation that has been extensively developed at PSI. The second-order closure method provides an excellent means to describe the response of boundary layer turbulence to strong pressure gradients. Also, the PSI model accounts for surface roughness effects, which can often be important as a result of extreme thinness of compression surface boundary layers. To account for the inviscid/viscous interaction process associated with separated flow regions, an inverse boundary layer calculation is being coupled to approximate descriptions for the inviscid flow.

The boundary-layer method that is being applied to compression-surface heating falls nicely between existing empirical methods and the heavily computational Navier-Stokes solutions of recent years, and hence should provide a valuable engineering approach. This approximate method will be applicable to control surface problems that arise with most supersonic aircraft and powered missiles, as well as to maneuvering re-entry vehicles.

2. TECHNICAL PROGRESS AND ACCOMPLISHMENTS

The objective of the research program is to develop approximate methods for analyzing two-dimensional and three-dimensional shock turbulent boundary-layer interaction heating on external aerodynamic configurations. Our basic approach for achieving this objective has been to develop a two-dimensional building-block model which will be used directly for 2-D interactions and will become an integral part of the 3-D interaction model. The focus of the work described in this report is the two-dimensional model.

2.1 Two-dimensional Compression Ramp Interaction Model

Our initial attack on the two-dimensional interactions concentrated upon utilizing the PSI boundary-layer codes (laminar and turbulent) which are finite-difference programs written in von Mises coordinates (streamwise coordinate X and stream function coordinate Ψ). These codes are suitable for non-interacting (specified pressure gradient) and unseparated flows. A direct application of the turbulent code to an unseparated turbulent case of Settles et al.[1] data showed reasonable agreement with skin friction behavior (Fig. 1) even though a crude linear pressure gradient was imposed upon the boundary layer. Of particular note is the ability of the code to compute the skin friction "well" near the corner. Even Navier-Stokes code calculations have experienced difficulties in this regard. Better approximations of the external pressure field using, for example, the scheme employed by Elfstrom[2] for hypersonic interaction studies, would be quite adequate for unseparated flows or incipient separated cases. The usefulness of the Elfstrom method resides in the use of the flat plate boundary-layer velocity profile approaching the corner. However, it is well known that such standard boundary-layer methods are not appropriate for interacting boundary-layer flows with separation and reattachment.

Direct boundary layer calculations for adverse pressure gradient flows with flow separation suffer difficulties due to the singular behavior of the skin friction near the point of separation (c.f. Goldstein[3]). Such conventional approaches cannot be utilized in regions of separated flow. The singular

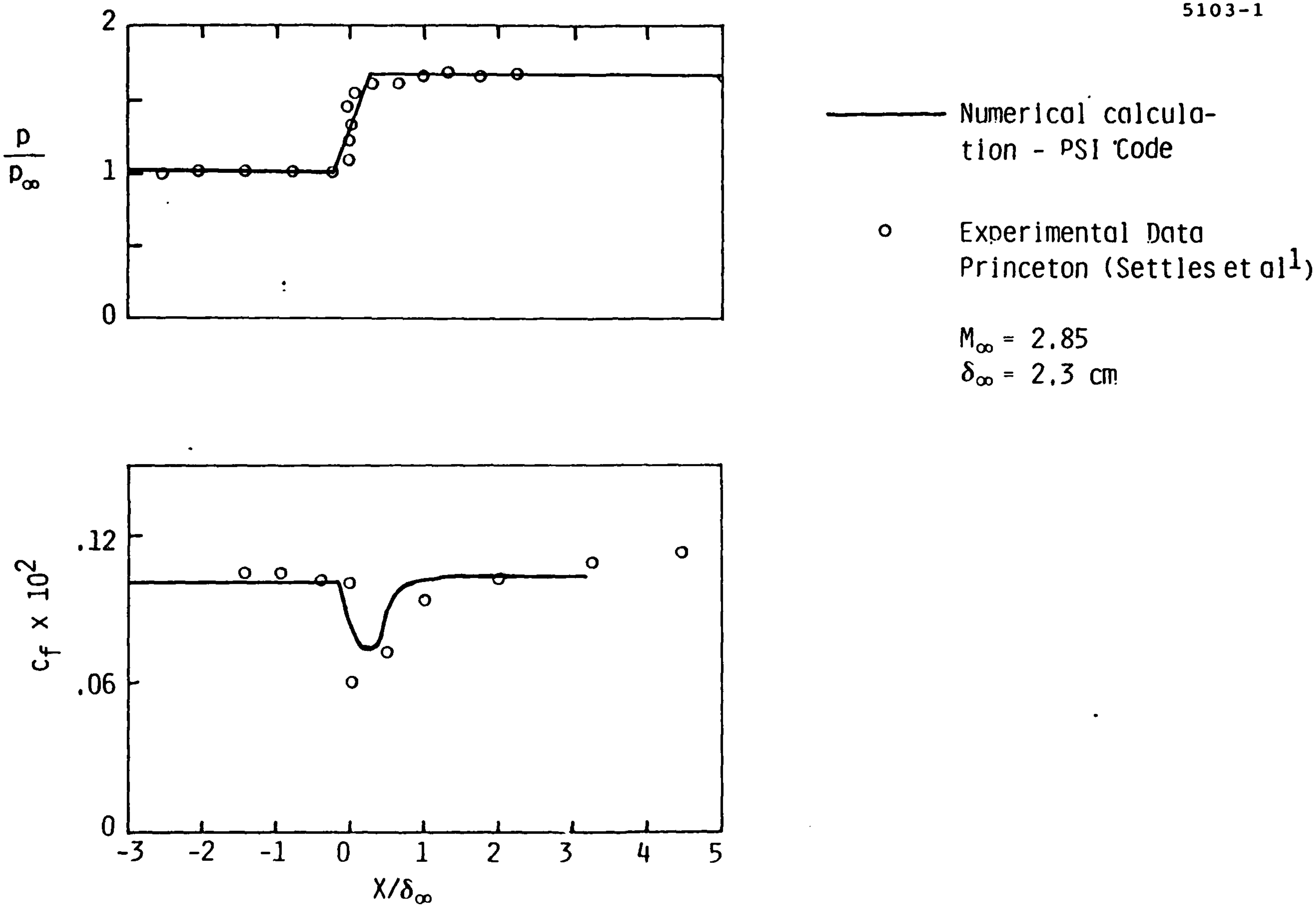

Fig. 1 Attached flow over 8° compression corner.

behavior can be eliminated by inverting the boundary-layer solution procedure and specifying the displacement thickness or the wall shear stress rather than the pressure gradient. This is a general statement applicable to both subsonic and supersonic flows. In supersonic flow, it is also possible to remove the separation singularity by doing direct viscous-inviscid interaction calculations that effectively modify the pressure distribution. The inverse boundary-layer procedure and the direct viscous-inviscid calculation have in common the requirement that the boundary layer interact with the inviscid flow. This interaction process is most conveniently treated by the so-called "semi-inverse" technique described by Wigton and Holt.[4]

The purpose of interaction calculations is to identify a consistent solution for both inviscid and viscous flows. Coupling algorithms perform this identification process. The literature contains two generic coupling schemes: inverse boundary-layer approach and, of course, the direct coupling scheme mentioned previously. The completely "inverse" technique utilizes an inverse boundary layer method in concert with an inviscid "design" approach wherein the geometry is sought for a specified pressure gradient. A more practical scheme is provided by the so-called "semi-inverse" method. The basic approach of the scheme is rather simple. One first computes the inverse boundary-layer flow given an approximate δ^* consistent with the flow configuration. Then one computes the inviscid flow past the shape that includes the same δ^*. Since, in general, these calculations will <u>not</u> yield the same pressure field, an algorithm must be identified to somehow update δ^* based upon physical, mathematical, or ad hoc arguments. Shock-wave boundary-layer interaction problems are ideally suited for the semi-inverse method. Hence, the philosophy of Wigton and Holt[4] has been adopted to guide a physically sound coupling algorithm development.

The Wigton and Holt[4] investigation was much needed. In particular, they showed that neither the approach of LeBalleur[5] nor the one of Carter[6] was logically sound. Both of these investigators have employed their techniques with success in treating transonic interaction problems, however both coupling formulas are at variance with the new study.[4] It was shown that the LeBalleur algorithm might fail to converge for attached boundary-layer flows and that

the Carter algorithm would be expected to diverge for separated supersonic flows. Accordingly, our coupling algorithms are based upon the sound, theoretically based study[4] which verified the above conclusions by convergence analysis and calculation. Since our interests are high-speed (supersonic and hypersonic) separated flows we will avoid the simple, but suspect, Carter[6] algorithm.

Substantial effort was undertaken to restructure the PSI codes into inverse boundary-layer codes. While convenient for many boundary layer applications, careful examination has led us to conclude that the stream-function coordinate is less appropriate for the interacting (and separating) flows than the physical (x,y) coordinates. The difficulties resided with the inability to force the satisfaction of the asymptotic stream function behavior at the boundary-layer edge. In addition, it appeared cumbersome to modify our approach to treat separation flows. For both of these reasons our previous boundary layer method was abandoned in favor of a more standard boundary-layer technique that allowed for the treatment of both inverse and separated configurations.

The adopted inverse boundary-layer technique is similar to that of Carter,[6] however since our emphasis is predominantly high-speed flows ($M > 2$), our inverse method is more suited to compressible flows. A Cartesian coordinate system, with the boundary-layer coordinate y scaled to the displacement thickness, is used in this inverse technique. The perturbation stream function approach[6] modified slightly to suit present needs, guarantees mass conservation and provides an explicit treatment of the displacement effect at the outer edge of the boundary layer.

Our inverse boundary-layer technique for laminar flow is defined by the following set of equations and boundary condition, for a perfect gas:

Momentum Equation

$$\bar{U} \frac{\partial \bar{U}}{\partial x} - \frac{1}{m} \frac{\partial \bar{U}}{\partial \eta} A = \left(\bar{T} - \bar{U}^2\right)\beta + \frac{1}{m\delta^*} \frac{\partial}{\partial \eta} \left(\frac{\mu}{\bar{T}} \frac{\partial \bar{U}}{\partial \eta}\right) \qquad (1)$$

Stream Function Equation

$$\frac{\partial \hat{\Psi}}{\partial \eta} = - m (\eta - 1 + t^*) \frac{\partial \bar{U}}{\partial \eta} \tag{2}$$

Energy Equation

$$\bar{U} \frac{\partial \bar{T}}{\partial X} - \frac{1}{m} \frac{\partial \bar{T}}{\partial \eta} A = \frac{1}{m\delta^*} \frac{\partial}{\partial \eta} \left(\frac{\mu}{\sigma \bar{T}} \frac{\partial \bar{T}}{\partial \eta}\right) + \frac{\mu}{\bar{T}} \frac{(\gamma-1) M_e^{\,2}}{m\delta^*} \left(\frac{\partial \bar{U}}{\partial \eta}\right)^2 \tag{3}$$

where the coefficient A is

$$A = \frac{\partial \hat{\Psi}}{\partial X} + m \bar{U} \frac{dt^*}{dx} + \bar{U} (\eta - 1 + t^*) \frac{dm}{dx} + m (\eta - 1 + t^*) \frac{\partial \bar{U}}{\partial x} \tag{4}$$

The perturbation stream function is defined by

$$\hat{\Psi} = \Psi - m\bar{U} (\eta - 1 + t^*) \tag{5}$$

where $t^* \equiv \int_0^\infty (\bar{T} - 1) d\eta$, η is the Dorodnitzyn-transformed y-coordinate scaled by δ^*, $\bar{T} = T/T_e$, $\bar{U} = U/U_e$, σ is the Prandtl number, $\beta = \frac{1}{U_e} \frac{dU_e}{dx}$, and $m = \rho_e U_e \delta^*$. The boundary conditions for the above equations are:

Wall $(\eta \equiv 0)$ $\quad \bar{U} = 0 \ , \quad \bar{T} = T_w/T_e$ (6.1)

Edge $(\eta \to \infty)$ $\quad \bar{U} \to 1 \ , \quad \hat{\Psi} \to 0, \ \bar{T} \to 1$ (6.2)

The inverse boundary-layer code requires the specification of the displacement thickness δ^* and the "displacement" mass flow $m = \rho_e U_e \delta^*$ in order to compute the unknown pressure gradient parameter β. The parameter m is particularly suited for interactive calculations with the inviscid flow since values of $\rho_e U_e$ are always available after each inviscid flow cycle.

The inverse problem is governed by two second-order (boundary-layer type) equations for $\bar{U}$ and $\bar{T}$, a first-order (continuity) equation for $\hat{\Psi}$, and

the appropriate boundary conditions enumerated above. These equations are solved numerically using the same implicit finite difference technique that we have used in our direct boundary-layer codes. Special care is required to determine the unknown pressure gradient. This is accomplished by invoking the continuity equation between the boundary-layer edge mesh point (N) and the neighboring interior point (N-1). The additional equation augments the block tridiagonal matrix inversion procedure in only a minor way.

The matter of describing separated or reverse flows is accomplished by invoking the Reyhner and Flügge-Lotz approximation.[7] This approximation permits integration through regions of reverse flow by neglecting streamwise convection in the separated flow region. It is a good approximation for thin, confined separated regions where $|U| \ll U_e$ and where the velocity and temperature vary slowly with downstream distance. High-speed compression corner separation regions are well described by this approximation and it is easily applied within our implicit finite difference solution algorithm.

The inverse boundary layer method was validated by comparing with results from a Navier-Stokes calculation and with calculations by Carter[8] using a different inverse boundary layer method. The problem investigated was the "modified" Howarth problem which encompasses a confined reverse flow region. The classical Howarth boundary-layer separation calculation involves an external flow with a linearly decreasing edge velocity. This flow intrigued many early analysts since the solutions exhibited the now "infamous" singular behavior at separation. Unfortunately, such flows separate and never reattach. In order to circumvent this behavior, the classical Howarth example was modified by maintaining the edge velocity to be constant beyond a point downstream of the standard separation point. This modification produces a nice confined separated flow region.

The Navier-Stokes calculation of this problem was undertaken by Briley.[9] His results for the displacement thickness were used as input for our calculation. Even our earliest results did exceptionally well in reproducing the separation and reattachment points. Extra care was needed to obtain a good agreement with the skin friction. This is important since the

skin friction variation is a very "sensitive" measure of understanding shock wave boundary-layer interactions. It was necessary to use a factor of three more mesh points (~ 91) than normally employed with attached boundary layers in order to have the inverse calculations agree with the reverse flow skin friction "well." Carter[4] performed a similar exercise with Briley's results. Our comparison with Carter's is also very good. The three calculations are compared in Fig. 2. Note in particular the excellent comparison of the separation and reattachment points with the previous studies. In Fig. 3 the shape factor δ^*/θ is compared with the Briley Navier-Stokes calculation. Once again the agreement is good. Finally in Fig. 4, we compare the velocity profile at the point of maximum reverse flow with that of Briley. This comparison is also very good. The maximum reverse flow velocity is less than 2% of the edge velocity for this case. It substantiates the validity of the Reyhner-Flügge-Lotz approximation. This exercise with the Howarth problem has thus established the utility of the inverse boundary-layer method and has provided necessary experience on the numerical accuracy requirements of the method.

The two-dimensional shock-wave boundary-layer interaction flows of primary interest to us occur at very high speeds (hypersonic conditions). Consequently, in order to treat such cases, a specific coupling algorithm has been developed for hypersonic flow interactions using the methodology of Wigton and Holt. The Newtonian flow approximation was utilized for the inviscid flow. The algorithm reads as follows:

$$(\delta^*)^{n+1} = (\delta^*)^n + a_1(u_{BL} - u_{INV}) + b_1\left(\frac{du_{BL}}{dx} - \frac{du_{INV}}{dx}\right) , \qquad (7)$$

where n is the iteration cycle index, u_{BL} and u_{INV} are the boundary layer velocity, and inviscid velocity, respectively, and a_1, b_1 are coefficients that depend upon boundary layer integral properties and displacement-surface slopes (and higher derivatives). The algorithm of Eq. (7) is more universal than both the Carter approach and the approach of LeBalleur. It has been incorporated into our computer model and specific data calculations are presently being undertaken.

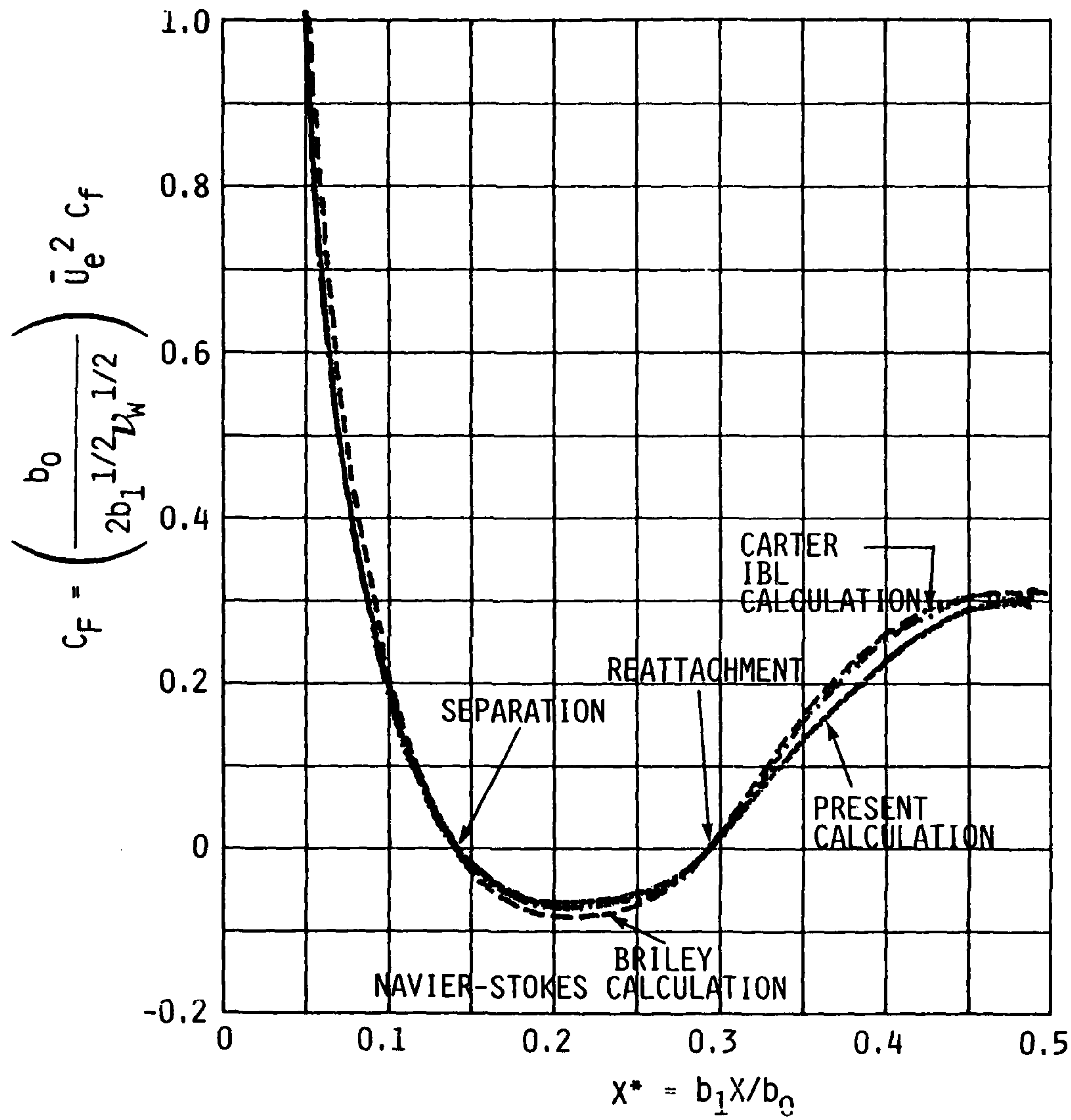

Fig. 2 Skin friction variation with downstream distance for the modified Howarth problem. C_F is the normalized friction parameter used by Briley with $U_e = b_o - b_1X$.

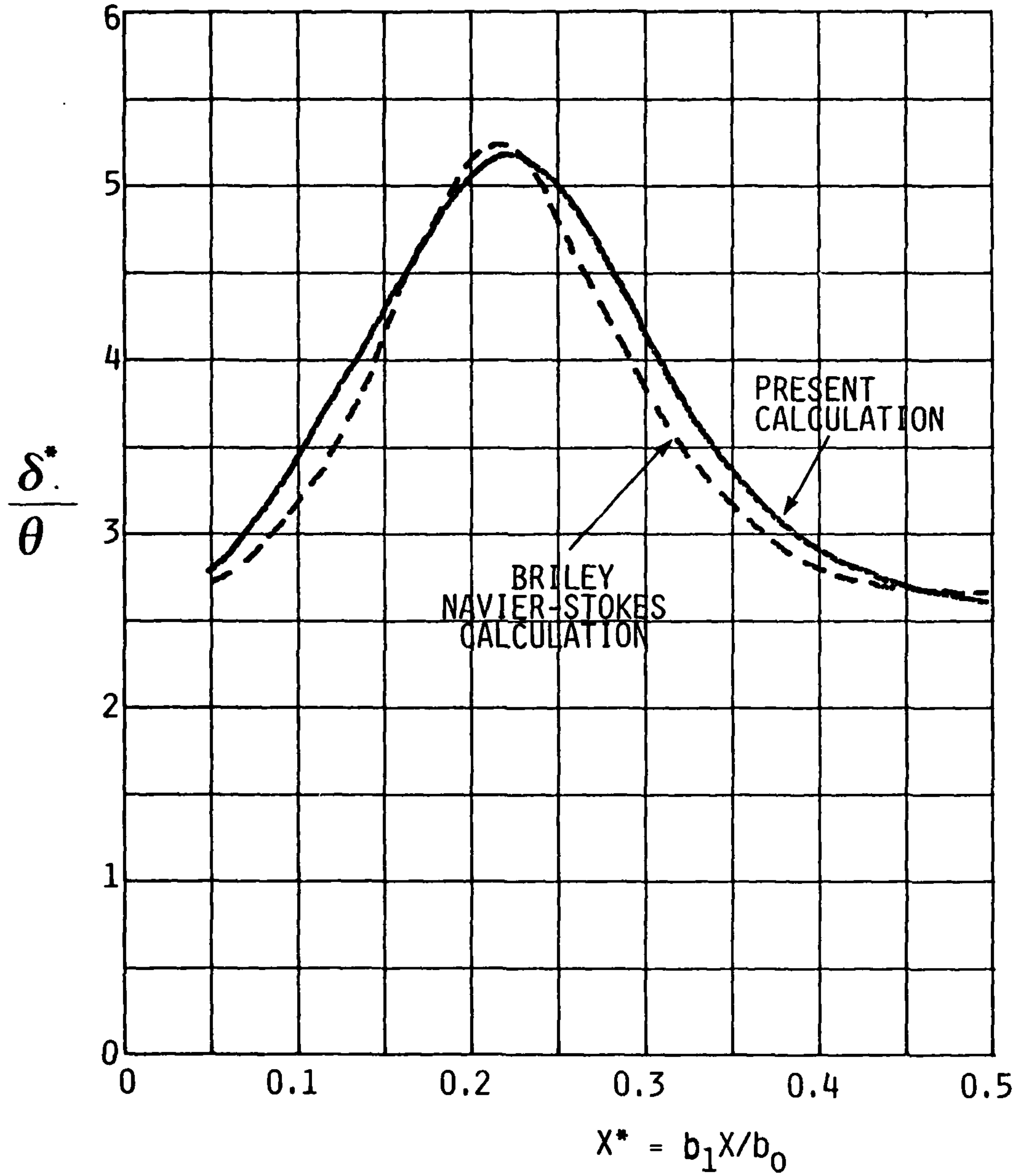

Fig. 3 Shape factor, δ^*/θ variation with streamwise distance.

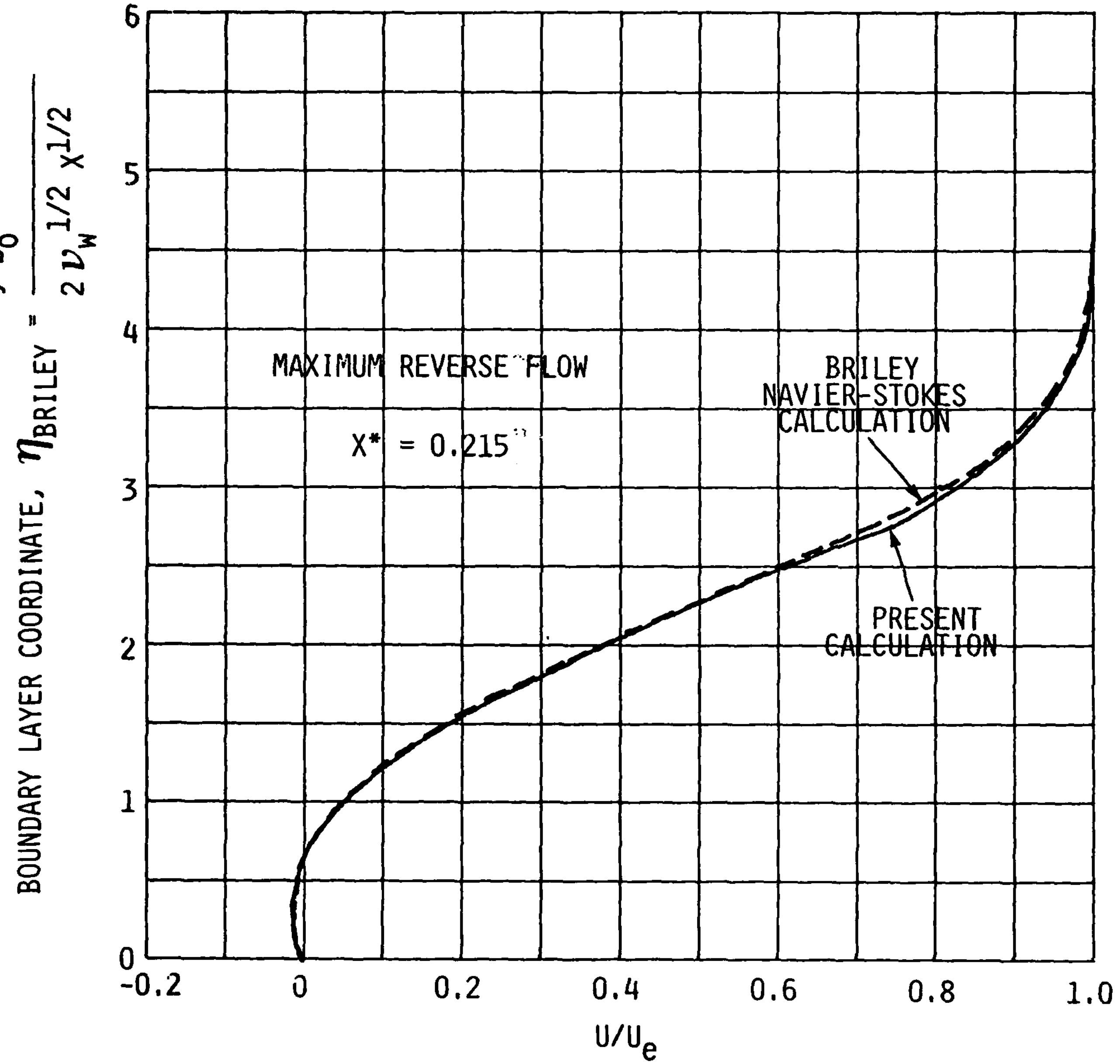

Fig. 4 Velocity profile comparison at maximum reverse flow.

The two-dimensional "building block" model will be validated against three sets of experimental data. The best laminar hypersonic compression surface data is that of Holden[10] at $M_\infty = 16$. His work includes excellent pressure (C_p), skin friction (C_f), and heat transfer (C_h) data for attached, mildly separated, and fully separated flow. Upon completion of these calculations, the turbulent compression corner experiments of Holden[11] at $M_\infty = 8.6$ and Settles et al.[1] at $M_\infty = 3$ will be computed.

A major test of the entire research effort is the separated turbulent flow data at $M_\infty = 8.6$. In fact, a particularly astounding state of affairs exists with respect to the experimental data taken by Holden[11] some nine years ago. He obtained data for four compression-corner deflection angles at $M_\infty = 8.6$; the smallest angle (27°) indicated incipient separation and the largest angle (36°) revealed extensive flow separation. No model calculations have been able to compute the characteristics of these four flows satisfactorily. The most concerted effort on these flows have emphasized the solution of the Navier-Stokes equations, but with relatively simple turbulence models. Hung and MacCormack[12] encountered difficulties in realizing the experimentally observed skin friction. They were a factor of two below the data peak at 27° and a factor of seven below the measured peak values for the 36° deflection angle case. Better agreement between such code calculations (Horstman et al.[13]) and experimental data (Settles et al.[1]) at $M_\infty = 3$ has been obtained; however, the skin friction was again difficult to predict. The disagreement between the computations and experiment increases with the degree of flow separation. The problem appears to be in the turbulence model equations. The NASA Ames group used zero-equation (algebraic eddy viscosity), one-equation (additional turbulence energy equation), and two-equation (additional turbulence length scale equation) model descriptions with varying degrees of success. It will be extemely interesting to see how well the interaction boundary-layer model with the more <u>comprehensive</u> <u>PSI</u> <u>turbulence</u> <u>model</u> compares against the experimental data. The inverse method is currently being incorporated into our rough-wall turbulent boundary-layer formulation.

2.2 Three-Dimensional Interaction-Region Heating

Three-dimensional shock wave boundary-layer interaction problems are generally quite complex and involve complicated shock patterns interacting with viscous separated surface flows. Such problems are best modeled exactly using Navier-Stokes codes with turbulence models and, indeed, the literature contains several such three-dimensional interaction calculations. However, the computational effort can easily be prohibitive. More approximate methods would find it very difficult to analyze these interactions. There are, however, several practical flowfields (c.f. Fig. 5) that appear amenable to "boundary-layer" analysis. These flows (e.g. swept compression corner and skewed fin) are similar in character and dominated by (quasi) two-dimensional behavior. This means that the essential physics of the interaction is controlled by the "locally" two-dimensional separation/reattachment process with the cross flow being a perturbative element in the analysis. Hence our two-dimensional model described above fits nicely as a "building block" component for the three-dimensional model.

We are investigating methods to treat these three-dimensional flows using an extension of the two-dimensional compression corner interaction approach. Our goal is to construct a quasi-two-dimensional formulation, in which the boundary-layer equations are solved in two dimensions, the plane normal to r in Fig. 5. Viewed in this plane, the three-dimensional shock-wave boundary-layer interaction problem is qualitatively similar to the two-dimensional compression corner case. To account for three-dimensional effects, the continuity equation will have to be modified to describe the mass flow in the r direction. A similarity approximation in this direction will probably be valid, given the common observation that separation lines are very straight. It may also be necessary to solve an integral momentum equation in the r direction. This type of approach is comparable to the method of semisimilar solutions for three-dimensional boundary-layer separation described by Williams.[14,15]

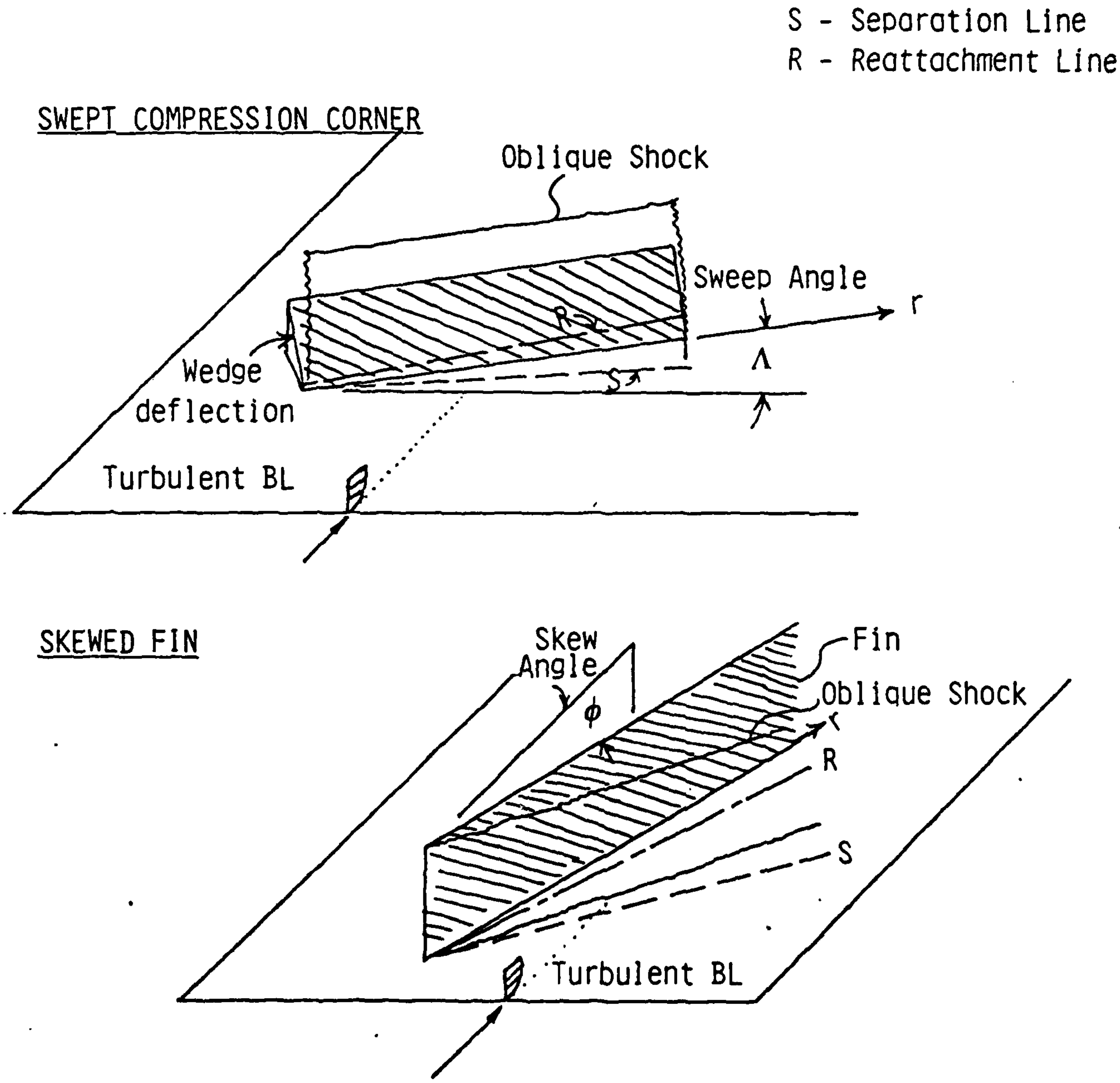

Fig. 5 Shock interaction flow fields.

3. TECHNICAL PUBLICATIONS, PRESENTATIONS, INTERACTIONS AND PERSONNEL

3.1 Chronological List of Technical Publications and Presentations

Finson, M. L. et al., "Advanced Reentry Aeromechanics Interim Scientific Report," Report PSI TR-10, AFOSR-TR-74-1785, 1974, Physical Sciences Inc., Woburn, MA.

Finson, M. L., "On the Application of Second-order Closure Models to Boundary Layer Transition," AGARD Conference on Laminar-turbulent Transition, AGARD Conference Proceedings No. 224, Oct. 1977, pp. 23-1 to 23-6.

Finson, M. L. and Wu, P. K. S., "Analysis of Rough Wall Turbulent Heating with Application to Blunted Flight Vehicles," AIAA Paper 79-008 (1979). Also PSI TR-158, AFOSR-TR-79-0199.

Finson, M. L., Clarke, A. S., and Wu, P. K. S., "Effect of Surface Roughness Character on Turbulent Boundary Layer Heating," PSI TR-204 (1979).

Finson, M. L. and Clarke, A. S., "The Effect of Surface Roughness Character on Turbulent Reentry Heating," AIAA Paper 80-1459, Snowmass, Co., 1980.

Finson, M. L., "A Model for Rough Wall Turbulent Heating and Skin Friction," AIAA Paper 82-0199, AIAA 20th Aerospace Sciences Meeting, Jan. 11-14, 1982, Orlando, Florida.

In preparation:

Legner, H. H. and Finson, M. L., "Hypersonic Shock Wave Boundary Layer Interactions," (in preparation for AIAA FPD meeting in July 1983 and publication in AIAA Journal).

3.2 Technical Interactions

An extensive study of the available rough wall boundary layer data was largely completed during the previous reporting period. Efforts during the current year have been limited to coordination with Dr. Michael S. Holden of Calspan and Dr. Anthony W. Fiore of the Flight Dynamics Laboratory regarding their planned experiments on rough surfaces at hypersonic speeds. We used our model to assist Dr. Holden in selecting the height and spacing of his "pattern" roughness (cones and hemispheres at three spacings each), and made pretest predictions to ensure that an interesting range of roughness augmentation would be observed.

The experiments at Calspan and the Flight Dynamics Laboratory are well underway and results should be available in the near future. The PSI model will be compared with those results, from which useful additional tests and/or model improvements will be suggested.

3.3 Technical Personnel

Dr. Michael Finson, Principal Investigator

Turbulence Modeling
Boundary Layer Transition
Effects of Roughness on Heating
Roughness Character
Heating Augmentation

Dr. Hartmut H. Legner

Viscous-Inviscid Interactions
Hypersonic Compression Flows
Three-dimensional Heating

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15. Williams, J. C., III, "Semi-Similar Solutions to the Three-dimensional Laminar Boundary Layer," Appl. Sci. Res. 31, 1975, 161-186.

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